Proceedings of Nuclear and Emerging Technologies for Space 2009
Atlanta, GA, June 14-19, 2009
Paper 208576

RADIATION CHALLENGES AND RISK MITIGATION FOR THE NUCLEAR-POWERED JUPITER EUROPA ORBITER MISSION

K. Clark*, T-Y Yan*, J. Boldt^, T. Van Houten*, I. Jun*, S. McClure*, R. Rasmussen*

**Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California*
^Applied Physics Laboratory, John Hopkins University, Laurel, Maryland

Corresponding Author: T-Y Yan; Tel: 818-354-3016; Fax: 818-354-0712; Email: yan@jpl.nasa.gov

Abstract – – *NASA and ESA have embarked on a joint study of a Europa Jupiter System Mission (EJSM) with orbiters developed by NASA, ESA, and possibly JAXA (Japan Aerospace Exploration Agency) to be launched no earlier than 2020. The NASA element of the joint endeavor, Jupiter Europa Orbiter (JEO), would be a nuclear-powered spacecraft designed to explore Europa and investigate its habitability. The proposed JEO includes a single orbiter flight system that travels to Jupiter by means of a multiple-gravity-assist trajectory. It is designed to function alone or in conjunction with ESA's Jupiter Ganymede Orbiter (JGO). The mission would conduct 30 months of Jupiter system science plus a comprehensive Europa orbit phase of 9 month period; thus addressing a very important subset of the EJSM science objectives. This paper focuses on the radiation challenges and risk mitigation for the proposed NASA-led JEO mission and describes a system-level radiation-hardened-by-design approach to mitigate pervasive mission and system level impacts.*

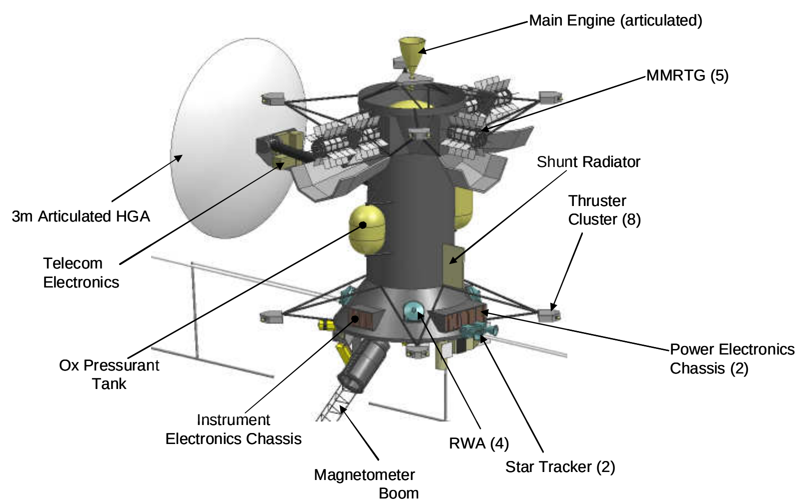

Figure 1: Conceptual design of the proposed nuclear-powered Jupiter Europa Orbiter (JEO) Flight System. The five (5) MMRTG – Multi-mission radioisotope thermal generators – are shown near the top right corner of the spacecraft.

I. INTRODUCTION

On February 18, 2009, National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), jointly announced the prioritization of the Outer Planet Flagship Mission (OPFM). It was decided that the Europa Jupiter System Mission (EJSM) would be the first to take the launch opportunity in 2020. The NASA element of the joint endeavor, Jupiter Europa Orbiter (JEO), would be a nuclear-powered spacecraft (Figure 1) designed to explore Europa and investigate its habitability. Planetary scientists have long been interested in such a mission with the goal of examining Europa's icy shell, studying the extent of its subsurface ocean and understanding its place in context with the Jupiter system.

The proposed JEO mission design and flight system concept draws upon the decade-long experience of refinements undertaken by the Europa Explorer (EE) Mission Studies (2007, 2006), Europa Explorer Design Team Report (2006), Europa Geophysical Explorer (2005) and Europa Orbiter (2001). The technology to fly such a mission has advanced over the past decade, especially in areas of launch vehicles, avionics, radioisotope power sources and detectors. While showing incremental improvements, the overall design has become remarkably mature and stable, suggesting that the requirements are well understood.

The proposed JEO spacecraft would spend a significant time in the harsh Jovian radiation belts in order to conduct scientific exploration. The primary challenge to a successful Europa orbital mission will be to protect the flight system from suffering life-threatening radiation damages for as long as possible. Designing for reliability and long life requires key knowledge of the environment, understanding of available hardware, conservative hardware and software design approaches, and a management structure that elevates the importance of radiation issues to the project office level. Instilling a system-level radiation-hardened-by-design approach early in the mission concept would help to mitigate the pervasive mission and system level impacts (including trajectory, configuration, fault protection, operational scenarios, and circuit design) that can otherwise result in run-away cost and mass growth.

The Jet Propulsion Laboratory (JPL), in partnership with the Applied Physics Laboratory (APL), has developed a four-year risk mitigation plan with the objective to retire the development and operational risks as early as possible prior to the start of Phase A development for the proposed JEO mission. Section II gives a brief introduction of the mission overview and flight system design. The following sections describe the systems engineering approach, the Jovian environment and radiation tolerant challenges posed by parts, material, circuit design, and sensors and detectors.

II. MISSION OVERVIEW AND FLIGHT SYSTEM DESIGN

The JEO mission concept calls for a single orbiter flight system that travels to Jupiter by means of a multiple-gravity-assist trajectory. Upon reaching Jupiter, JEO would conduct a 30-month Jupiter system science investigation plus a comprehensive 9-month Europa orbit phase. The JEO mission science objectives, as defined by the international EJSM Science Definition Team (SDT), include:

a) Europa’s Ocean: Characterize the extent of the ocean and its relation to the deeper interior
b) Europa’s Ice Shell: Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange
c) Europa’s Chemistry: Determine global surface compositions and chemistry, especially as related to habitability
d) Europa’s Geology: Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration
e) Jupiter System: Understand Europa in the context of the Jupiter system

A summary of the proposed JEO trajectory, tour, and Europa orbit parameters is in Table I.

TABLE 1

Baseline Mission Design Characteristics

Parameter	Value
Launch Vehicle	Atlas V 551
Earth to Jupiter Trajectory	VEEGA
Earth Launch Period	2/29/2020 to 3/20/2020
C_3 (km^2/s^2)	Up to 12.8
Interplanetary Deep Space ΔV (m/s)	Up to 93
Jupiter Arrival Date	12/21/2025
Declination of Launch Asymptote (deg)	<2
Jupiter Arrival V_∞ (km/s)	5.5
Jupiter Orbit Insertion (JOI) Earth Range (AU)	4.3
JOI Periapsis Altitude (R_J)	5.2
Jupiter Capture Orbit Period (days)	~200
Jovian Tour	12/21/2025 to 7/3/2028
Europa Orbit Insertion (EOI)	7/3/2028
Primary Europa Science	7/3/2028 to 3/30/2029
Orbit Altitude, Average (km)	200, then 100
Orbit Period (min)	138, then 126
Ground Speed (km/s)	1.2, then 1.3
Orbits/day	10.4, then 11.4
Europa Initial Orbit Inclination (deg)	95

Achieving the aforementioned Europa science objectives mandates tight pointing spacecraft requirements for this mission. In addition, power requirements imposed by the instrument and telecommunications subsystem, as well as the harsh radiation environment (>5X the dose of the Juno mission), strongly favors the use of radioisotope power sources over solar array power systems at these distances. Five Multi-Mission Radioisotope Thermal Generators (MMRTGs) would provide approximately 540W of electrical power for the spacecraft at the End of Mission (EOM). Redundant 12-Ah Lithium-ion batteries would provide for energy storage to handle transient demands for power throughout the mission, such as during Europa Science orbit when science instruments simultaneously operate and communicate back to Earth. In order to reduce electrical power that would otherwise be allocated for heaters, waste heat from the MMRTGs is used for thermal control to the maximum extent practical. Radioisotope Heater Units (RHUs) and Variable RHUs would also be used for the same reason. There are several design considerations related to the MMRTGs. They are:

- Accommodation of 5 MMRTGs and the 3m High Gain Antenna (HGA) inside the Atlas V fairing envelope and its access door size and number;

- Placement of MMRTGs with respect to each other and to science instruments; and
- Plume impingement and coupling requirement of eight thruster clusters on instruments, HGA, and MMRTGs.

As shown in Figure 1, the proposed JEO flight system configuration is developed with general modularization in mind. The modules include: the lower equipment module (top module in the diagram) which houses the MMRTGs; the core structure that primarily houses the propulsion system; the electronics bus which houses wall electronics (except for the telecom electronics which are located behind the HGA); and the instrument deck that houses all the instruments. This approach provides for ease of integration and the potential benefit to partition development. A summary of JEO flight system parameters is shown in TABLE II.

TABLE II
Baseline JEO Flight System Configuration

Flight System Parameter	Value
Wet Mass (43% system dry mass margin)	5,040 kg
Dry Mass (including 25% contingency)	1,714 kg
Model Payload (Current Best Estimate)	106 kg, 172W (CBE)
MMRTG (five total); battery for peak power	540W
Two-axis Gimbaled High Gain Antenna	3 m
Downlink Data Rate to 34m at Ka-Band	150 kbps
Peak Science Data Volume	7.3 Gb per day
Bi-propellant MON/MMH Propulsion System	2,260 m/s
Rad-hardened electronics design point behind100 mil (Al)	2.9 Mrad
Doppler Ttracking	two way at X/Ka band
Ultra Stable Oscillator (Allen Deviation)	$< 10^{-13}$
Electronics Shield Mass	192 kg (CBE)
Planetary Protection	Bioburden reduction plus radiation environment
Lifetime	9 years

III. CONVENTIONAL VS SYSTEMS ENGINEERING DESIGN FOR HIGH RADIATION ENVIRONMENT

The Jovian harsh radiation environment presents significant technical challenges for designing a long duration mission to Europa. Data collected from seven prior spacecraft flybys of Jupiter (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Cassini, and New Horizons) as well as the Galileo orbiter indicate that the radiation exposure of electronic parts may reach as high as 3 Mrad (±0.5 Mrad) (Si) dose behind 100 mils of aluminum during the entire mission lifetime. Undoubtedly, the radiation dose level, transient noise and dose rate effects experienced would be unprecedented for NASA missions.

Early risk assessment and mitigation activities can severely impact the development and operational costs associated with challenging missions. Therefore, it is paramount to assimilate design methodologies and considerations for long duration missions early in the planning and conceptual cycle. The proposed JEO mission design capitalizes on Galileo's remarkable discoveries and leverages significantly on its technical know-how. The Galileo orbiter provided JPL with the unique opportunity of operating a scientific spacecraft in the most intense regions of the radiations belts. Concomitantly, invaluable experience gained from Juno and Radiation Belt Storm Probes (RBSP) led by APL (both scheduled to be launched in 2011) will benefit the formulation of the proposed JEO mission during Phase A and Phase B of the development.

The Galileo mission design followed the conventional JPL engineering practice in which mission designers multiplied the estimated total ionizing dose (TID) level by a radiation design factor (RDF) of 2. The resultant 2X environment was used for the selection of parts, materials, detectors and sensors for radiation susceptibility and shielding designs. This conventional approach (as illustrated in Figure 2) results in mission designs that function well beyond the intended design environment. For example, Galileo's mission was extended three times with the spacecraft accumulating an estimated radiation dose of at least 8 times its design level. This estimate is derived from science data collected during the Galileo mission[1,2] although there was no dosimeter on board to measure the actual environment. At the end of Galileo's 8-year mission, the spacecraft was still functioning.

In the conventional approach a basic trade made in the design for radiation environment is one of shield mass versus lifetime. Many elements influence the trade space including parts and material capability, shield mass composition, natural shielding by moons or other spacecraft elements (e.g., propulsion tanks), and even component placement within assemblies. The systems-engineering approach expands the trade space and recognizes the advantages of identifying and utilizing excessive margins in the development chain from parts selection, design of electronic subsystems and final system integration.

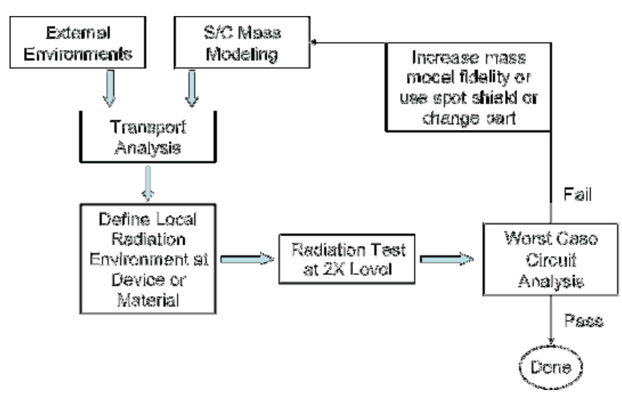

Figure 2. Conventional radiation shielding design approach focuses on tradeoffs between shield mass and lifetime based on selection of parts and materials

Table III

Conventional versus Systems engineering Approach for Harsh Radiation Environment

Attribute	Conventional Approach	Systems-Engineering Approach
1. Application	1. Applied to Galileo mission and New Frontier Juno Jupiter mission	1. Will be applied to Jupiter Europa Orbitor (JEO)
2. Mission Design	2. Based on limited prior knowledge of radiation environment from Pioneers and Voyagers	2. Optimized trajectory to takes advantage of better radiation knowledge including Europa self shielding effects
3. Shielding Approach	3. Centralized vault (e.g., Juno approach) protects the electronic assemblies.	3. Distributed/Strategic approach to avoid shielding the "lowest common denominator" part tolerance level
4. Annealing of Radiation Damage	4. Passive only in Galileo	4. Passive and active – where parts may be heated to accelerate recovery
5. Radiation Tolerance Test Data	5. Limited to low radiation requirements (<50 krad) and short life times (<5 years) with little if any characterization of tolerance above these levels.	5. Needed to extend to 1 Mrad and address low dose rate effects
6. Worst Case Analysis (WCA)	6. Conducted with Extreme Value Analysis even where it is virtually impossible condition could occur.	6. Relaxed to reflect realistic mission conditions.
7. Electronic Components	7. Restricted to fabrication processes and parts level radiation tolerance capabilities	7. Many components (e.g., ASIC) now available are radiation hardened by design up to 1 Mrad
8. Reliability Systems Engineering	8. Generally ignores science objectives and potential graceful degradation.	8. Explicitly includes science value, fault protection and contingency plans to facilitate graceful degradation.
9. Reliability Assessment	9. Limited to parts and circuit level.	9. Extended to system-level enabling trade studies,risk analysis and management of margins.

Table III compares and contrasts the design process of the systems-engineering approach proposed for the JEO mission against that of the conventional approach. Clearly, the system oriented approach demonstrates a cross-discipline design. As in the conventional approach, the mission design starts with quantifying the radiation environment for the mission given the initial trajectory. However, in the systems engineering approach, the spacecraft trajectory is adjusted to lessen the radiation impact without sacrificing the science objectives, or to permit acceptable increases in TID; thus maximizing the likelihood of achieving specific science objectives.

Recent advances in electronics for military and nuclear applications have made many parts available up to several hundred krad (Si). These newly available components and fabrication processes, coupled with more thorough testing and characterization along with careful circuit configuration and layout will significantly enhance the robustness of the flight system and thus extend the lifetime of the proposed JEO mission.

A prudent parts selection process, disciplined circuit design methodology and formal reliability testing procedures are areas that a mission designer could enforce to strengthen the radiation-hardened capability. Unlike the conventional radiation shielding design as shown in Figure 2, the optimum shield effect can be achieved at the spacecraft system level by strategic placements of shielding boxes and communally shield assemblies of similar radiation-hardness. This distributed/strategic approach significantly reduces shielding mass when compared to a centralized design where a single vault (e.g., Juno approach) would be used to shield all electronics. The advantage of the systems engineering approach was demonstrated and presented for simple spacecraft geometry at the 1st OPFM Instrument Workshop held in Monrovia, California, June, 2008. A detailed trade study will be performed in future development phases to determine the optimum shielding design and placement.

As shown in Table III, the proposed system design methodologies incorporate reliability results from lower levels into systems engineering analysis. This will quantify the overall design lifetime and manage margins, providing tremendous insight into prioritizing science collection, designing fault protection and developing contingency plans to ensure graceful system degradation. These system-level implications could then be optimized in trade studies and risk analysis. Based upon the conventional design approach, the JEO would have a mission lifetime lasting to the end of Europa Campaign 3 (105 day in Europa orbits). However, the mission designer would not be able to provide any information about the likelihood of surviving beyond the 105 days. On the other hand, the systems engineering approach captures the state of the JEO design in a system lifetime model that demonstrates that the system will function well beyond Europa Campaign 3. There are ample design margins that show the JEO mission would likely be operational up to one-year and beyond in the Europa orbit. Therefore, the proposed JEO end of prime mission is conservatively defined as 9 months after the Europa Orbit Insertion (EOI), around July, 2028.

IV. JOVIAN ENVIRONMENT MODEL

The proposed JEO mission is subjected to four major radiation sources: (1) solar energetic particles (protons, electrons, and heavy ions) during the interplanetary cruise, (2) galactic cosmic rays (protons and heavy ions) during the interplanetary cruise, (3) trapped particles (electrons, protons, and heavy ions) in the Jovian magnetosphere during the Jupiter tour and the orbits at Europa, and (4) particles (neutrons and gammas) from the onboard nuclear power source, MMRTG.

Among the four radiation sources, the high-energy trapped electrons and protons at Jupiter are the dominating contributors to the "life-limiting" TID and displacement damage dose (DDD) effects. The single event effects (SEE) due to solar particles and cosmic rays are not unique to the proposed JEO mission. The Jovian trapped particles are not static, but vary in intensity and population spatially and temporally. Correctly defining and characterizing the radiation environments allow the mission designer to optimize JEO tour and orbital trajectories; thus constraining the radiation exposure to an affordable design level. The JEO design would include a radiation dosimeter to monitor the field radiation exposure in real-time. Data accumulated will allow validation of the environment and shielding modeling effort.

IV.A. Reference Radiation Design Point for JEO

The Jovian radiation environment model used for JEO is a semi-empirical model based on data collected from Pioneers 10 and 11, Voyagers 1 and 2, and Galileo. Specifically, it is the Divine model augmented by the Galileo high energy electron data[3]. In addition, the Galileo data are also used to predict a statistical radiation environment[2]. These data, together with a theoretical calculation, was carried out specifically to characterize the environment in the near vicinity of Europa[4]. Figure 3 shows the reference TID depth curve developed for the proposed JEO mission. The reference radiation design point is 2.9 Mrad(Si) behind a 100 mil (2.5 mm) aluminum shield. This mission TID level includes 1.25 Mrad expected for the Europa orbital portion (corresponding to 105 days at Europa with the conventional RDF=2).

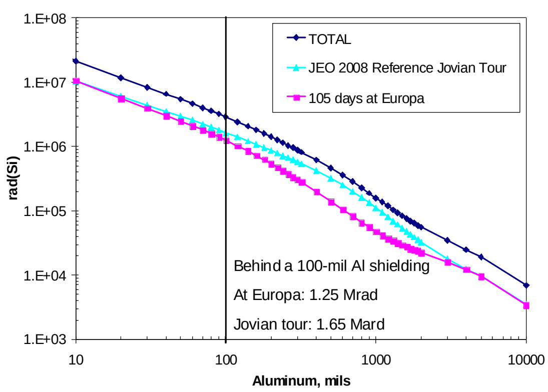

Figure 3. JEO Reference Total Ionizing Dose (TID) Depth Curve shows the reference radiation design point for the proposed JEO Mission. There is no radiation design factor (RDF) included in the reference plot (i.e., RDF = 1)

IV.B. Shielding for JEO

Electronic assemblies are vulnerable to failure when exposed to a high radiation environment for long durations. Though many parts are functional after exposure, the parameter degradation may be different from typical parameters shown on specification sheets from vendors. The availability of radiation tolerant parts from 100 krad to 1 Mrad tolerance and electronic design architectures make a Europa mission much more viable when JPL first started Europa mission studies 10 years ago. Figure 4 shows the estimated shielding mass, given device TID capability for the proposed JEO mission. There will be a severe mass penalty if everything is shielded for the lowest radiation tolerant part. In addition, Figure 4 also illustrates that there will be a "diminished return" if the mission designer over-specifies the parts requirements.

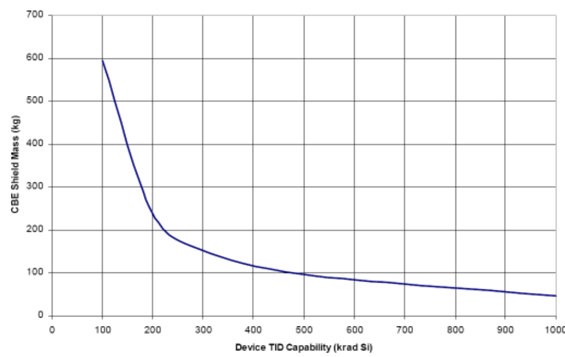

Figure 4. Total shielding mass as a function of parts capability. There will be a severe mass penalty if everything is shielded for the lowest radiation tolerant part. This figure also demonstrates the "diminished return" if the mission designer over-specifies the parts requirements. For the JEO mission, device TID capability of 300 krad is a good compromise between the shielding mass and parts capability.

The selected JEO approach would allow flexibility for different part tolerance levels (100 krad to 1 Mrad) to avoid having to shield everything down to the "lowest common denominator" part tolerance level. It also allows for placement of electronics in strategic locations, such as the Traveling Wave Tube Amplifiers (TWTAs) on the back of the HGA. As the design matures and the part radiation tolerance becomes better known, this trade will be periodically re-evaluated to take advantage of the most mass efficient approach. Some of these shielding strategies to be considered include:

- Placement of components within an enclosure (e.g., sensitive components on cards in center of stack of 6U chassis),
- Incorporating structural mass (e.g., propellant tanks) into shield model,
- Selecting less sensitive components (e.g., batteries) to shield more sensitive devices,
- Physically locating assemblies of similar rad-tolerance and using single enclosure (e.g., as used in Telecom shielding),
- Layering of shield materials (High Z and Low Z).

In the current JEO design, all electronics packaged on standard 6U cards would use a shielded chassis to reduce the radiation dose to one half the part-level tolerance value; thus satisfying the conventional radiation design point of RDF=2. For pre-packaged electronics or sensors/detectors, shielded enclosures are used instead. Figure 5 illustrates the concept of shielding for enclosures, chassis and spot shielding. Based upon the Master Equipment List (MEL) of the proposed JEO flight system, the majority of the part tolerance level is specified to be a minimum of 300 krads. The exceptions are the propulsion system pressure transducers, which are rated for 75 krads, and the Space Inertia Reference Unit (SIRU), which is rated for 200 krads. Other subsystems such as Small Deep Space Transponder (SDST) and some individual assemblies may require additional localized shielding to reach the tolerance level as specified. The power electronics and mass memory are both rated for a 1 Mrad dose, and the MMRTGs are capable of withstanding multi-Mrads of dose.

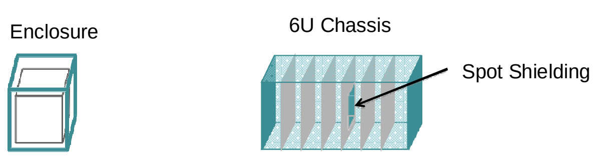

Figure 5. Shielding Concept: Blue sides illustrate the radiation shielding for pre-packaged electronics (enclosure shielding), for standard 6U format cards (chassis shielding), and spot shielding as needed.

The Current Best Estimate (CBE) of the spacecraft shield mass using Tungsten-Copper is 192 kg, comprised of 59 kg for payload instrument detector and electronics shielding, and 132 kg for engineering electronics shielding. With the current design, the Tungsten-Copper provides over 20% mass saving over aluminum and over 5 times saving in terms of shield volume. Spot shielding estimates for sensitive components such as the star tracker detector are included. The thermal, structural and mechanical subsystems include no radiation sensitive components, and thus do not require any additional shielding.

V. PARTS AND MATERIAL CHALLENGES

The availability and selection of electronic parts for radiation susceptibility and reliability presents the first hurdle to be overcome. Commercially available radiation tolerant parts from 100 krad to 1 Mrad are not generally used or tested for long duration missions. The majority of NASA's radiation test and life test data on electronic parts has been taken in support of missions with low radiation requirements (<50 krad) and short lifetimes (<5 years). Therefore, parameter degradations due to high radiation exposure levels have not been fully characterized and documented. Consequently, there is limited data to support parts selection, Worst Case Analysis (WCA), and determination of risk areas for aggressive radiation environments such as those experienced by the proposed JEO mission. Thus, all electronic assemblies on the flight system would need to be redesigned to incorporate these radiation-hardened parts. Analyses and packaging would need to be re-examined.

V.A. Device Assessment for JEO

The radiation susceptibility, reliability, and availability are crucial areas where early evaluation, testing, and characterization would be pivotal for prudent radiation tolerant designs. In particular, the following device technologies have been identified as critical for the proposed JEO flight system. They are equally important, if not more for the instrument providers. TABLE IV lists six device technologies that would require assessments prior to Phase A of the development in these three areas.

TABLE IV

Radiation Assessment of Device Technologies

Device Technology	Radiation Susceptibility	Reliability	Availability
Non-Volatile Memory	✓	✓	
FPGA		✓	✓
Power Converter	✓	✓	
μProcessor μController	✓	✓	
Data Bus Device			✓
Linear Device	✓		

Another issue requiring attention is overly conservative radiation test and analysis methods, which could quickly exhaust the resources available for missions with very high radiation environments. Typical missions employ worst case conditions for testing to ensure that mission conditions are bounded and these conditions do not impose stressful design constraints. For the proposed JEO mission, however, these existing test and evaluation methods can result in excessive conservatism in the development of worst case design parameters and significant unnecessary costs for radiation testing. In addition, as part of the lessons learned from the Galileo experience, the JEO mission would mandate a low dose rate testing intended to address Enhanced Low Dose Rate Sensitivity (ELDRS) for susceptible parts, especially bi-polar devices. However, a typical ELDRS test is carried out at dose rates between 5 and 10 mrad/s. At these dose rates, tests for missions with dose levels in the hundreds of krads would take longer than one year. These tests must be started in early in the development cycle to accommodate their long-lead times so that their results can be included in the flight system design.

Similarly, typical test methods and analyses for total dose in Complementary Metallic Oxide Semiconductor (CMOS) devices do not allow for annealing or other life extending effects (e.g., dormancy). On long duration missions, some parts could survive higher TID if annealing is considered. This has been an accepted rationale for some of the extra functionality of the Galileo spacecraft during the Jupiter encounter. Recent test results conducted as part of the risk mitigation effort at JPL have confirmed similar behavior in the laboratory. Presently no guideline or method exists to address the benefit of annealing to extending device performance. The systems engineering approach employed by the JEO mission designers would address such clear sources of over-conservatism in tests and analytical methods.

V.B. Material Selection Guideline for JEO

The selection guidelines of materials for radiation susceptibility and reliability has been documented in a report entitled, “Materials Survivability and Selection for Nuclear Powered Missions” by Willis[6]. The material used on Composite Overwrapped Pressure Vessel (COPV) tanks can stand radiation to take surface doses in the anticipated radiation environment without loss of strength for the JEO environment. Dose-depth curves of aluminum, silicone rubber, Teflon FEP, Kynar (polyvinylidene fluoride), polyimide (e.g., Kapton and Vespel), PEEK (polyether-ether ketone), silica, sapphire, and tantalum, parametrized by different energy ranges, are provided in the aforementioned report. This includes many soft goods used within electric valves in the propulsion subsystem.

V.C. Approved Parts and Material List for JEO

Recognizing the unprecedented level of radiation possibly encountered by the proposed JEO mission, the JPL and APL team has developed a process of identifying and approving standard parts for flight equipment (engineering and instrument providers) under the project’s cognizance. The Approved Parts and Materials List (APML) will be populated with a wide assortment of electrical, electronic, and electromechanical (EEE) parts and materials, as well as many critical parts such as sensors, detectors, power converters, Field Programmable Gate Arrays (FPGAs) and non-volatile memories. Each entry will be accompanied with a Worst Case Datasheet (WCD) and application notes describing proper use of the part at selected radiation levels. Dissemination of this information early in the design process is critical to enable engineering and instrument providers to adequately design for the harsh radiation environment.

Every approved part listed on the APML will meet the applicable reliability, quality, and radiation requirements specified in the “Parts Program Requirements (PPR)”[7]. The APML will accept parts at four (4) radiation levels: 50, 100, 300, and 1000 krad. The APML would be updated quarterly as new radiation data become available. Parts not listed as approved on the APML are defined as non-standard parts and will require a Non-standard Part Approval Request (NSPAR) for use in JEO. All non-standard parts will be reviewed, screened, and qualified to the requirements of PPR.

Every part on the APML will be approved by the Parts Control Board (PCB), co-chaired by both JPL and APL parts program managers. The PCB recommends and approves parts for inclusion in the APML. Criteria will be based on absolute need, the number of subsystems requiring the part, qualification status, TID, SEE, and procurement specification review. Mission designers should use standard parts to the maximum extent possible so that they can reduce the radiation testing and qualification expenditure to the minimum.

Currently the APML has included over 148 EEE parts, 70 WCDs, and 130 materials for spacecraft components. The list will be updated as new parts and materials become available. Figure 6 shows a sample page of the APML.

Flight Part #	Parts Status	SEL/ SEGR/ SEB	SEU	SET	SEFI	DD	50K	100K	300K	1000K	NSPAR Number	Planetary Protection
5962F9568901VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T		
5962F9666302VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T		
5962F9568902VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T		
5962F9563201VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T		
5962F9563101VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	T		
5962H0151704VXC	A	A	A	S	A	A	A/WCD	A/WCD	A/WCD	A/WCD		
5692R9663601VXC	A	A	A	S	A	A	A/WCD	A/WCD	T	N		
5962R9664101VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N		
5962R9661401VXC	A	A	S	A	A	A	A/WCD	A/WCD	T	N		

Figure 6. Sample page of the APML – includes description of the device, device type, part number, packaging, sustained radiation dose level, SEE and planetary protection compliance.

VI. RADIATION TOLERANCE DESIGN CHALLENGES

Following customary JPL engineering practice, a parts data base is constructed to include degradation due to radiation, power supply variation, end-of-life, and part-to-part variation for each component parameter. Often an additional safety margin is levied on the part parameters. The traditional approach of conducting a Worst Case Analysis (WCA), using extreme value analysis (EVA) based on these part parameters, exaggerates the difficulties of the circuit design by requiring that it still functions when subjected to the worst possible combination of part parameters, each at its extreme value. Typically, parts on the same board are assumed to be at different temperature extremes if it drives the worst-case scenario, even if it is virtually impossible that this could occur.

In the event that the initial circuit fails to meet the WCA, for example, due to radiation effects, one approach is to provide spot shielding for the component. However, in designing the spot shield, the packaging engineer is often required to shield to an RDF of 3 instead of 2 in order to allow for higher uncertainties in the shielding analysis. Consequently, due to a compounding effect of conservatism at several levels, a traditional flight system and electronics subsystem design will contain excessive margins that limit resources available for mission science.

To counter these effects and allow a better use of resources across the system, WCA methods will be refined in otherwise marginal cases to eliminate unrealistic cases and to consider, where appropriate, the true statistical nature of parametric variations. Furthermore, these analyses will be conducted concurrently with design and selective radiation tests to assure that circuits are making the best accommodation for device characteristics over their lifetime.

The baseline approach for all electronics on the flight system is to use Application Specific Integrated Circuits (ASICs) instead of FPGAs. It is evident from Table IV that this is a more conservative approach until FPGAs can be adequately evaluated for both TID tolerance and SEE mitigation. The advantages in using FPGAs as intermediate products in developing complex ASICs for flight has prompted the development of guidelines for selection, design, and validation of appropriate FPGAs to support this process. The proposed JEO mission will require improved design methodologies and guidelines to demonstrate the ability of flight engineering subsystems to operate in the Europa radiation environment.

VII. SENSORS AND DETECTOR CHALLENGES

Radiation-induced effects on instrument detectors and other key instrument components ultimately impact the quality and quantity of the mission science return and the reliability of engineering sensor data critical to flight operations. High-energy particles found within the harsh Europa environment would produce increased transient detector noise as well as long-term degradation of detector performance and even potential failure of the device. Transient radiation effects are produced when an ionizing particle traverses the active detector volume and creates charges that are clocked out during readout. Radiation-induced noise can potentially swamp the science signal, especially in the infrared wavebands where low solar flux and low surface reflectivity result in a relatively low signal to noise ratio (S/N). Both TID and DDD effects produce long-term permanent degradation in detector performance characteristics. This includes a decrease in the ability of the detector to generate signal charge or to transfer that charge from the photo active region to the readout circuitry; shifts in gate threshold voltages; increases in dark current and dark current non-uniformities; and the production of high-dark-current pixels (hot pixels or spikes). It is important to identify and understand both the transient and permanent performance degradation effects in order to plan early for appropriate hardware and operations risk mitigation to insure mission success and high-quality science returns.

JPL/APL had formed a Detector Working Group (DWG) to perform an initial assessment on detectors and laser components considered by notional payload instruments and stellar reference unit (SRU). The assessment included the following technologies: visible detectors, mid-infrared and thermal detectors, micro-channel plates and photomultipliers, avalanche photodiodes, and laser-related components (pump diode laser, solid-state laser, fiber optics). For each technology, the DWG (i) reviewed the available radiation literature and test results, (ii) estimated the radiation environment incident on the component behind its shield, and (iii) assessed the total dose survivability (both TID and DDD) and radiation-induced transient noise effects during peak flux periods.

The DWG concluded that the radiation challenges facing the JEO notional payload instruments and SRU detectors and laser components are well understood. With the recommended shielding allocations, the total dose survivability of these components is not considered to be a significant risk. In many cases, the shielding allocation was driven by the need to reduce radiation-induced transient noise effects in order to meet science and engineering performance requirements on the S/N. For these technologies — notably mid-infrared detectors, avalanche photodiode detectors, and visible detectors for star tracking — the extensive shielding (up to 3-cm-thick Tantalum) for transient noise reduction effectively mitigates all concern over total dose degradation. For the remaining technologies, more modest shielding thicknesses (0.3–1.0 cm Tantalum, depending upon the specific technology) were judged to be sufficient to reduce the TID exposure and transient noise impact to levels that could be further reduced by other known mitigation techniques such as better detector design, refined detector operational parameters and improved algorithmic approaches.

However, DWG cautioned that inferring detector performance in the Jovian environment based on existing radiation test results could be pre-mature. The irradiation species may not be representative of the JEO concept's expected flight spectra. A rigorous "test-as-you-fly" policy with respect to detector radiation testing, including irradiation with flight-representative species and energies for TID, DDD, and transient testing, would be necessary for the proposed JEO mission.

VIII. RISK MITIGATION EFFORT

Radiation risk is the single largest technical challenge for any Europa mission. The conventional approach in designing and verifying spacecraft flight electronics subsystems in the harsh radiation environment often leads to excessive design margins and severely underestimates the mission lifetime. This commonly results from a compounding effect of applying worst-case assumptions at every level: from parts selection to system design and engineering. JPL has attended to this deficiency by developing a system-level approach of quantifying the uncertainties through rigorous analysis and validation through laboratory testing. The resulting multi-year Risk Mitigation Plan[8] has defined a pathway by which radiation risks would be addressed in a systematic manner; while performing quantitative trades in the mission and science value space.

Efforts are already underway to retire the majority of risks related to the parts and materials, electronic designs and radiation-induced effects on sensors and detectors as well as to develop design guidelines. A total of 27 design documents and tutorials that potential instrument providers could use to mitigate their design risks were delivered to NASA as part of the 2008 JEO Mission Study[5]. Many of these deliverables have been made public via the Outer Planets Flagship Mission website http://opfm.jpl.nasa.gov. Several of the documents are International Traffic in Arms Regulations (ITAR) sensitive. Publically releasable versions of these documents are in the process of being made available. The approach described in the Risk Mitigation Plan[8] has been endorsed by the latest NASA findings of the TMC (Technical Management Cost) panel reviewing the 2008 JEO Mission Study[5].

In the Risk Mitigation Plan[8], realistic mission conditions and design guidelines will be developed to improve the traditional process while simultaneously providing an accurate picture of estimated mission lifetime. The plan includes the development of design tutorials, the APML and radiation design guidelines for potential instrument providers; assessment of radiation effects on sensors and detectors of science instruments; evaluation of the availability of radiation-hardened parts such as FPGA, memory, and power converters; identification and more thorough testing of electronic parts; measurements of these parts under various dose rate effects; and establishment of a mission lifetime estimation methodology when subjected to different radiation effects based on the electronic parts database.

There are six major elements in the work plan. They are:

1. System Reliability Model;
2. Environment and Shielding Models;
3. Radiation Design Methods;
4. Sensors and Detectors;
5. Parts Evaluation & Testing; and
6. Approved Parts and Materials List.

The near term goal of this work plan is to support the 2nd Instrument Workshop (planned for summer 2009) and the release of a structured proof-of-concept system model, which includes identifying required input information in 2010. Additional design information is planned for public release during the pre-phase A as part of a strategy to reduce cost risk for both engineering and instrument providers. The 3rd Instrument Workshop is planned to take place in the summer of 2010. It would be followed by the release of instrument Announcement of Opportunity (AO) tentatively scheduled for December 2011.

IX. CONCLUSIONS

NASA announced the prioritization of the 2020 launch opportunity for its Outer Planet Flagship Mission (OPFM). The Europa Jupiter System Mission (EJSM) was chosen to be the next interplanetary expedition investigating the Jupiter system. The mission is rated "low risk" in terms of mission implementation by the NASA TMC review panel, which implies that there is a well-planned course to mitigate risks posed by radiation challenges. It will take approximately two years of pre-Phase A activities in order to retire anticipated risks as discussed in the Risk Mitigation Plan[8].

The JPL/APL team has capitalized on prior deep space flight experience while exercising a systems engineering approach to uncover hidden design margins throughout the development chain. The proposed JEO design leverages on the experiences gained from Galileo, as well as the on-going New Frontier Juno Jupiter and Radiation Belt Storm Probes (RBSP) missions to be launched in 2011. The radiation tolerance design approach discussed in SECTION VI would provide sufficient protection of electronic assemblies to the end of the JEO prime mission.

While JPL focuses on mitigating risks as outlined in the Risk Mitigation Plan[8], there are other potential risks in the areas of programmatic, political (both domestic and international) and finances that could derail the development. In contrast, the science objectives are well defined by the international Science Definition Team (SDT) and the challenges posed by the harsh Jovian radiation will remain unchanged.

Technical challenges posed by the Jovian environment can be met with a thorough and well-executed radiation risk mitigating plan. Understanding the hidden margins embedded in the conventional design for radiation protection and using them to design a robust spacecraft with a better grasp of mission lifetime requires attention at the system level. This systems-engineering approach improves the traditional process and provides a more accurate method of estimating mission lifetime. The method captures the graceful degradation behavior of mission lifetime beyond Europa Science Campaign 3 (after 105 days), which would not be possibly quantified under the conventional approach.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the hard work completed by all of the members of the JJSDT, the NASA JEO study team, and the ESA JGO study team.

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